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ELECTRICAL SUPPLY FOR MFTF-B SUPERCONDUCTING MAGNET SYSTEM*

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Abstract

The MFTF-B magnet system consists of 42 superconducting magnets which must operate continuously for long periods of time. The magnet power supply system is designed to meet the operational requirements of accuracy, flexibility, and reliability. The superconducting magnets require a protection system to protect against critical magnet faults of quench, current lead overtemperature, and overcurrent. The protection system is complex because of the large number of magnets, the strong coupling between magnets, and the high reliability requirement. This paper describes the power circuits and the components used in the design.

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INTRODUCTION

The magnet power supply system for the Mirror Fusion Test Facility (MFTF-B) provides regulated direct current for 42 superconducting magnets (Figure 1).[1,2] Plasma is contained in the central-cell solenoids (WS6-ES6) using high field solenoids (A2, A1) and yin-yang plugs (M1, M2) at each end. Transition magnets (T1, T2) are used to match the circular field pattern of the central cell to the elliptical field pattern of the yin-yang plugs. Eight trim magnets (TR1-TR8) are used in the transition region on each end to precisely align the magnetic fields.[3] Magnet A2 is composed of two magnets, an outer solenoid (A20) which uses NbTi conductor and an inner solenoid (A2I) which uses Nb_3Sn conductor to achieve a high (12T) on-axis field. All the other magnets are single magnets using NbTi conductor. The magnets vary greatly in size from the 113 MJ yin-yangs to the 0.1 MJ trim magnets. Operating currents vary from 6278 A for transition magnet T2 to 900 A for the trim magnets.

REQUIREMENTS AND DESIGN GOALS

The MFTF-B magnets are planned to be on continuously for 13 weeks during the 18-week physics operational cycle. Physics shots last for 30-seconds every five minutes. The time allotted for fully energizing and fully de-energizing the magnets is four hours for the 26 main magnets and five minutes for the 16 trim magnets. Control of each magnet current must be done individually over limited ranges with the exception of the central solenoids which can be controlled in groups. The absolute error in control of the magnet currents must be within $\pm 1\%$.

In addition to the physics operational requirements, several requirements and design goals exist because the magnets are superconducting. Circuitry must

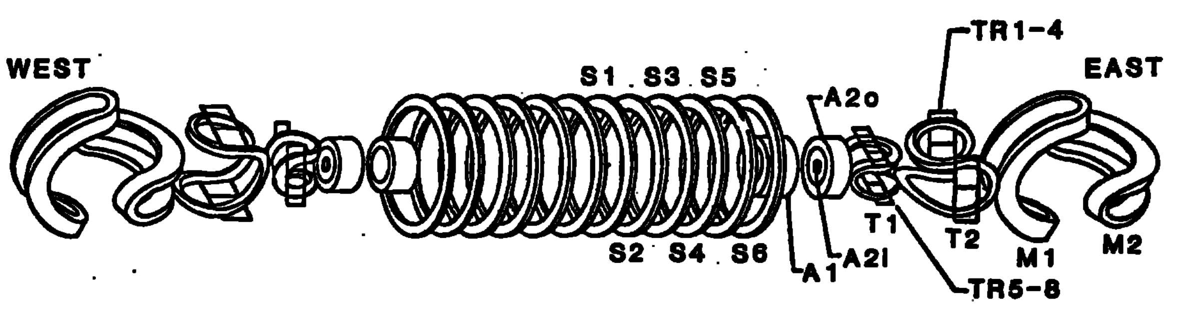


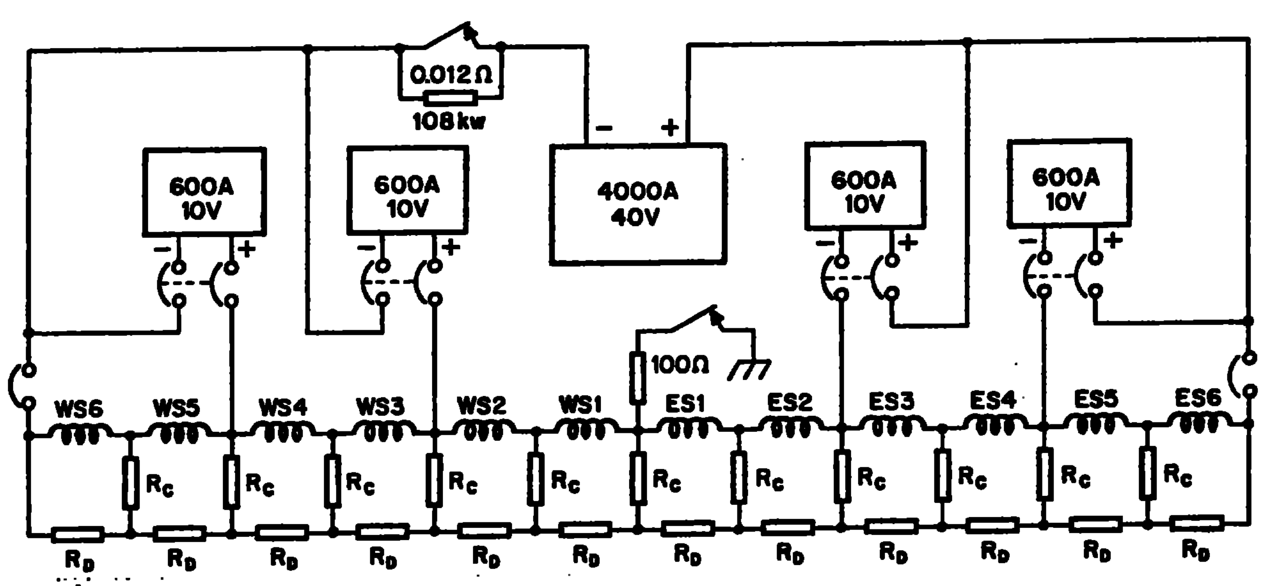
Figure 1. MFTF-B Magnets

be provided to de-energize rapidly (fast dump) the magnets in event of critical faults including quench, current lead overtemperature, and induced overcurrent. Induced currents caused by magnetic coupling between magnets and rapidly forming quenches must be limited to avoid large mechanical structures and supports. The goal for limiting induced currents is I_{pk}/I_{oper} = 1.00 when surrounding magnets quench and the fast dump protection circuitry operates properly, and I_{pk}/I_{oper} = 1.22 when the fast dump circuitry fails to operate. The magnet design limits the voltage to ground during fast dump to 500 V or less and the peak conductor temperature to 200 K during a quench. Because of possible damage to the magnets and/or long downtimes in event of a failure in the protection system, redundancy must be used in the critical fault monitoring and in the fast dump protection circuitry.

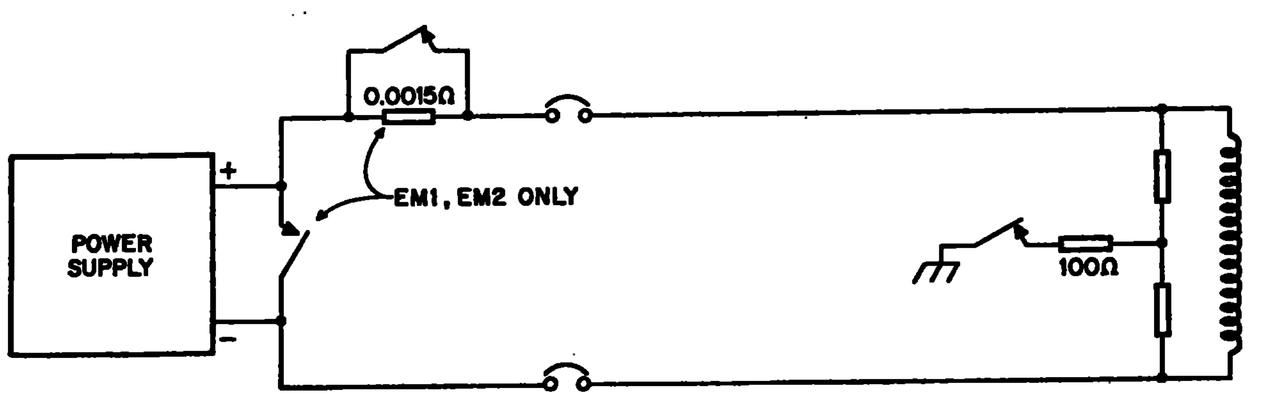
DC POWER CIRCUITS

There are four types of power circuits which are used for supplying the 42 magnets (Figure 2). Common to each circuit are high energy resistors across each magnet and a 100 ohm grounding resistor. Magnets are connected in series and supplied from a main power supply and one or more trim power supplies wherever possible to minimize dc cabling and circuit breaker costs.

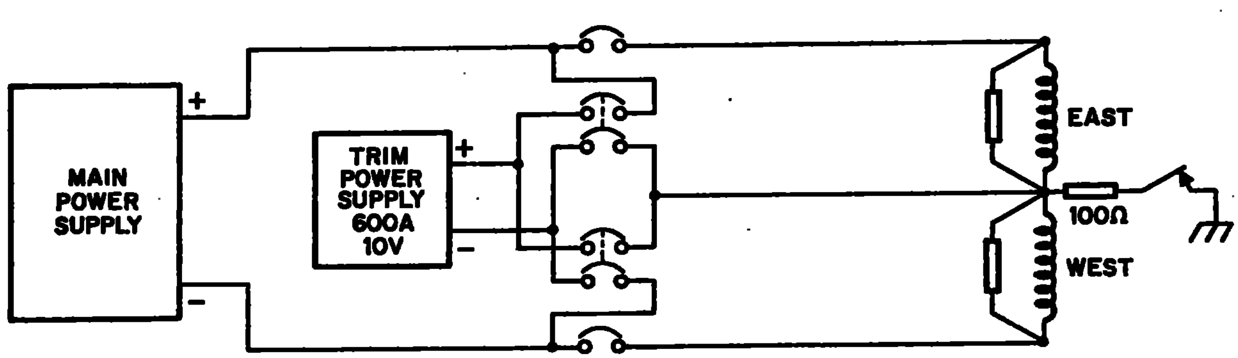
The circuit for magnets ES6–WS6 consists of one main power supply and four trim power supplies. The trim power supplies are required to increase the field from 1T at central solenoids ES1 and WS1 to 1.6T at the end solenoids ES6 and WS6. DC circuit breakers are used to interrupt the power circuit in the event of a critical magnet fault. The magnet currents are forced into the dump resistors (R_d) connected in parallel with the magnets. Redundant main dc circuit breakers are used to provide high reliability. Coupling resistors (R_c) are used in addition to dump resistors to limit the peak induced currents to 1.22 times the operating current during a quench of adjacent coils and a failure of the dc circuit breakers to open.[4] During fast dump the voltage to ground is 500 V for the end solenoids. Because of the high inductance of the 12 series solenoids (82 H), an additional 0.012 ohm resistor is inserted using a contactor during normal de-energizing to achieve the four-hour decay time.



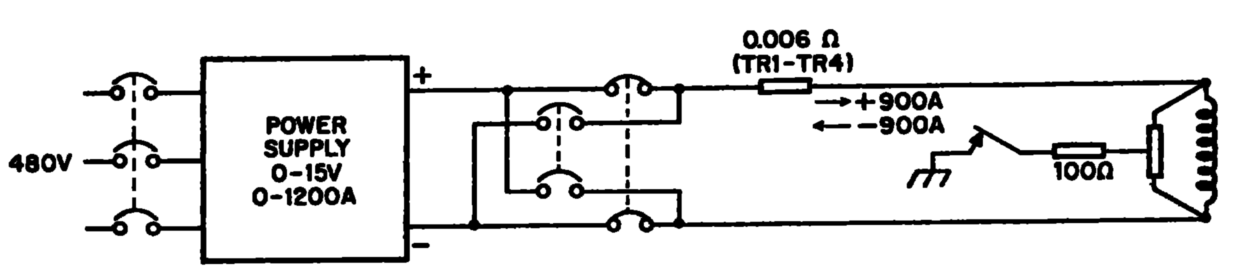
(a) ES6-WS6



(b) EM1, EM2, WM1, WM2, EA2I, WA2I



(c) ET2, WT2; ET1, WT1; EA20, WA20; EA1, WA1



(d) ETR1-8, WTR1-8

Figure 2. Power Circuits

East and west magnets T2, T1, A20, and A1 are connected in series and supplied from one main power supply. A smaller trim power supply is available for connection either to the east or west magnets to permit adjustment for differences. Magnets EM2, EM1, WM2, WM1, EA2I, and WA2I have their own power circuits. This is to allow grounding of the center of the fast dump resistors and thereby maintain a voltage to ground of 500 V or less. Constraints on temperature rise of the magnet conductor and induced currents during a quench resulted in dump resistor values too high to permit the east/west series connection. The circuits for EM1 and EM2 differ from the other single magnet circuits because they were built for the original MFTF configuration tested in 1981.[5]

The trim magnets ETR1-8 and WTR1-8 have separate power circuits to enable full adjustment of each current individually. Each power circuit includes a polarity switch to enable either polarity of field adjustment. The circuits for trim coils TR1-4 also include a series resistor to limit induced currents during a quench of magnet T2. Because of the low inductance of the trim coils, the fast dump protection mode is not needed and turnoff of the power supplies is adequate to protect against critical faults. For redundancy, the input ac circuit breakers are tripped in event a critical fault occurs and the power supplies fail to turn off. Resistors are connected across each trim magnet to protect against an accidental open circuit.

Table 1 lists several key parameters and component values of the magnets and power circuits. The energy E_{max} includes the energy stored in the mutual inductances as well as the self inductances.

TABLE 1. MAGNET AND POWER CIRCUIT PARAMETERS

Coil	Max Current	L_{Self}	E_{Max}	R_D, R_C	V_{Coil}	$V_{Coil-Gnd}$	Time Constant(L_{Self})
WM2	4410 A	11.11 H	113.0 MJ	.085 Ω	375 V	187 V	131 sec
WM1	3837	11.11	88.4	.085	326	163	131
WT2	6278	2.71	57.8	.040	251	251	68
WT1	5266	.77	14.0	.040	211	211	19
WA20	4648	6.02	77.2	.055	256	256	109
WA2I	1504	3.77	11.6	.50	752	376	8
WA1	4208	6.02	63.9	.055	231	231	109
WS6-ES6	2866	3.61	27.4	.029	83	499	124* R_D(12 Units)
			20.0	.029			R_C(11 Units)
EA1	4208	6.02	63.9	.055	231	231	109
EA2I	1504	3.77	11.6	.50	752	376	8
EA20	4648	6.02	77.2	.055	256	256	109
ET1	5266	.77	14.0	.040	211	211	19
ET2	6278	2.71	57.8	.040	251	251	68
EM1	3837	11.11	88.4	.085	326	163	131
EM2	4410	11.11	113.0	.085	375	187	131
WTR1-4 ETR1-4	900	0.46	0.2	.250	225	112	2 (8 Units)
WTR5-8 ETR5-8	900	0.28	0.1	.250	225	112	1 (8 Units)

*Actual Time Constant including mutual inductances = 250 sec

SUBSYSTEMS AND COMPONENTS

A dedicated 480 V, three-phase substation rated at 1300 kVA supplies the 35 magnet power supplies and associated controls. Thirty-three power supplies were supplied by Dynapower Corporation and the two power supplies for EM1 and EM2 by Robicon Corporation.

The thirty-three new power supplies consist of two 8000 A, four 6000 A, one 4000 A, two 2000 A, sixteen 1200 A, and eight 600 A units. The voltage ratings vary from 6 V to 40 V and are determined by the magnet inductance and the four-hour energizing time requirement. The power supply current ratings are all at least 20% higher than the actual operating currents to provide high reliability. Primary thyristor control is used with a double-y, secondary rectifier circuit. These components are water cooled. A natural air-convection cooled free-wheeling diode is also used at the output to provide a path for the magnet current in event of cooling water failure (Figure 3). The power supplies are unfiltered and are voltage regulated with a maximum error of 2%.

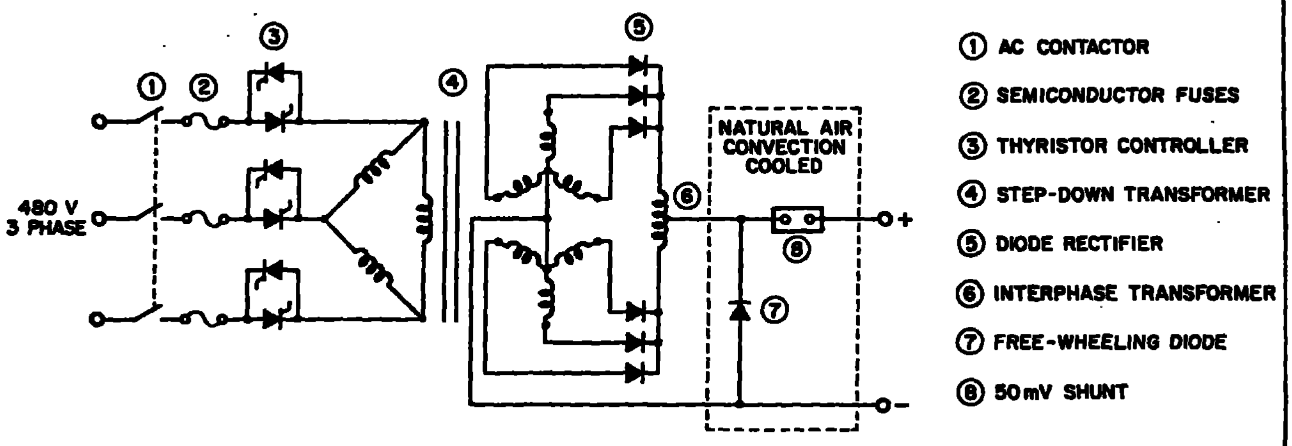


Figure 3. Power Supply Circuit

Twenty-two one-pole dc circuit breakers were supplied by Brown-Boveri and consist of two 8000 A, fourteen 6000 A, two 4000 A, and four 1600 A units. These dc circuit breakers are semi-high speed class and rated for an 800 Vdc circuit voltage. The circuit breaker close and trip controls are supplied from a 120 Vdc battery system which enables trip operation during utility power outages. The trim power supply dc circuit breakers consist of 600 A, 250 Vdc molded case, two-pole breakers with motor operators for remote control of position. All breakers are tripped simultaneously in event of a critical magnet fault to prevent induced currents from exceeding operating currents. The trim coil polarity switches each use two 1000 A, 250 Vdc molded case, two-pole breakers with motor operators. These switches are not tripped when the breakers in the main coil power circuits are tripped during fast dump. Change in position of the trim power supply breakers or trim coil polarity switches occurs only near zero current.

The fast dump and coupling resistors, are all naturally air-cooled, neutral grounding type resistors. They are designed to absorb and dissipate the energy stored in the magnets with a temperature rise of 610°C or less. The resistance values of the resistors were carefully selected to meet requirements on magnet conductor temperature rise, voltage, and induced currents. This was done using computer simulations of the magnets, including mutual coupling, and power circuits during fast dump and magnet quench conditions.

Series resistors in the EM1, EM2, ES6-WS6, and TR1-TR4 power circuits are rated for continuous-duty with a temperature rise of 375°C. The resistors for EM1, EM2, and ES6-WS6 are bypassed with switches except during de-energizing of the magnets. Their resistance values are selected to meet the four-hour decay time requirement. The resistance of the series resistors in the TR1-TR4 power circuits was selected using computer simulations to limit the induced currents to 1.22 times the maximum operating currents during worst-case quench conditions.

The 100 ohm grounding resistor in each power circuit ties the center point in the circuit to ground. The magnets and dc power circuits are isolated and must pass routine high-pot tests at 2000 Vdc. The selection of 100 ohms is a tradeoff between high resistance which limits damage to the magnet in event of a magnet ground fault and low resistance which overcomes imbalances due to stray capacitance and resistance. The voltage across each 100 ohm resistor is monitored in the computer-based control system to enable detection of ground faults. A relay contact is in series with each ground resistor to permit remote high-pot tests to be performed.

The power supplies, circuit breakers, switches, and continuous-duty resistors are located between 100 and 300 feet from the magnets on the outside of a concrete vault which contains the magnets and vacuum vessel. The fast dump, coupling, and grounding resistors are located inside the vault below the vacuum vessel. Cabling between the power supplies, circuit breakers, switches, continuous-duty resistors, and magnets consists of type RHH cable rated at 600 V in aluminum cable tray. Penetrations through the seven-foot thick vault wall consist of copper bus bars. Cables from the magnets to the fast dump, coupling, and grounding resistors are transient-duty rated based on the appropriate fast dump time constant. These cables are contained in aluminum conduit and follow a routing different than the continuous-duty cable run. This minimizes the chance of accidently open-circuiting a magnet.

CONTROLS

The control system for the magnets and power circuits uses isolation amplifiers, analog circuits, relays, and several computer-based controllers. The control system provides automatic control of the magnet currents and automatic protection of the superconducting magnets. Redundancy is used to provide highly reliable detection of a critical magnet fault and to accomplish the appropriate power circuit response. Based on the type of fault and the severity, the power circuit will respond by stopping energizing of the magnets, de-energizing slowly, or fast dumping.

Magnet current control is done using an analog feedback controller. Current setpoints from the computer-based controllers and power supply current and magnet voltage feedback signals are combined to control the voltage setpoint to each power supply. Because of the high degree of electrical coupling and magnetic coupling between magnet voltages and currents, the feedback controller was designed as a multivariable controller with dynamic decoupling.[6]

CONCLUSIONS

A complex, highly reliable dc power system is required for the MFTF-B superconducting magnets. Major design drivers are the need to protect against critical magnet faults and the strong mutual coupling between magnets. The design goals were achieved using conventional equipment, over-rating components, properly sizing and placing of resistors, and using redundant dc circuit breakers and associated controls. The design and fabrication of most components has been completed and they are currently being installed.

REFERENCES

1. S.T. Wang, et. al, "The MFTF-B Superconducting Magnet System," Proc. 9th Int. Cryogenic Engineering Conf. Kobe, Japan (May 11-15, 1982).

2. S.T. Wang, et. al, "Progress on Axicell MFTF-B Superconducting Magnet Systems," Proc. 10th IEEE Symposium on Fusion Engineering, Philadelphia, PA (Dec. 5-9, 1983).

3. G.T. Yamaguchi, D.E. Baldwin, "Trim Coils and Magnet Alignment in MFTF-B, "Proc. 10th IEEE Symposium on Fusion Engineering, Philadelphia, PA (Dec. 5-9, 1983).

4. E.W. Owen, et. al., "Alternative Power Supply and Dump Resistor Connections for Similar, Mutually Coupled, Superconducting Coils," Proc. 10th IEEE Symposium on Fusion Engineering, Philadelphia, PA (Dec. 5-9, 1983).

5. T.A. Kozman, et. al., "Magnets for the Mirror Fusion Test Facility: Testing of the First Yin-Yang and the Design and Development of Other Magnets," Proc. The Applied Superconducting Conference, Knoxville, Tenn. (Nov. 30-Dec. 3, 1982).

6. E.W. Owen, D.W. Shimer, "Multivariable Current Control for Electrically and Magnetically Coupled Superconducting Magnets", Sixth Topical Meeting on the Technology of Fusion Energy, San Francisco, CA (Mar. 3-7, 1985).